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Introduction to MPI

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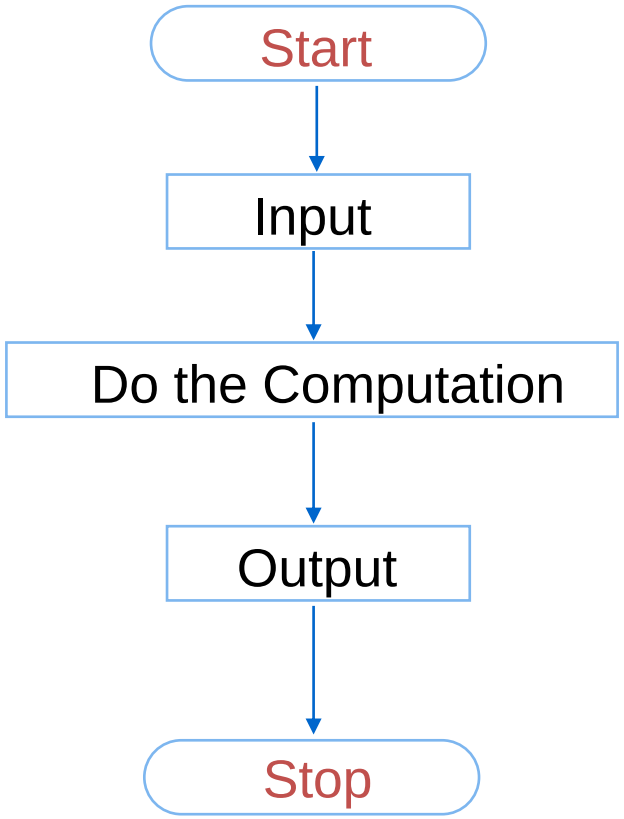
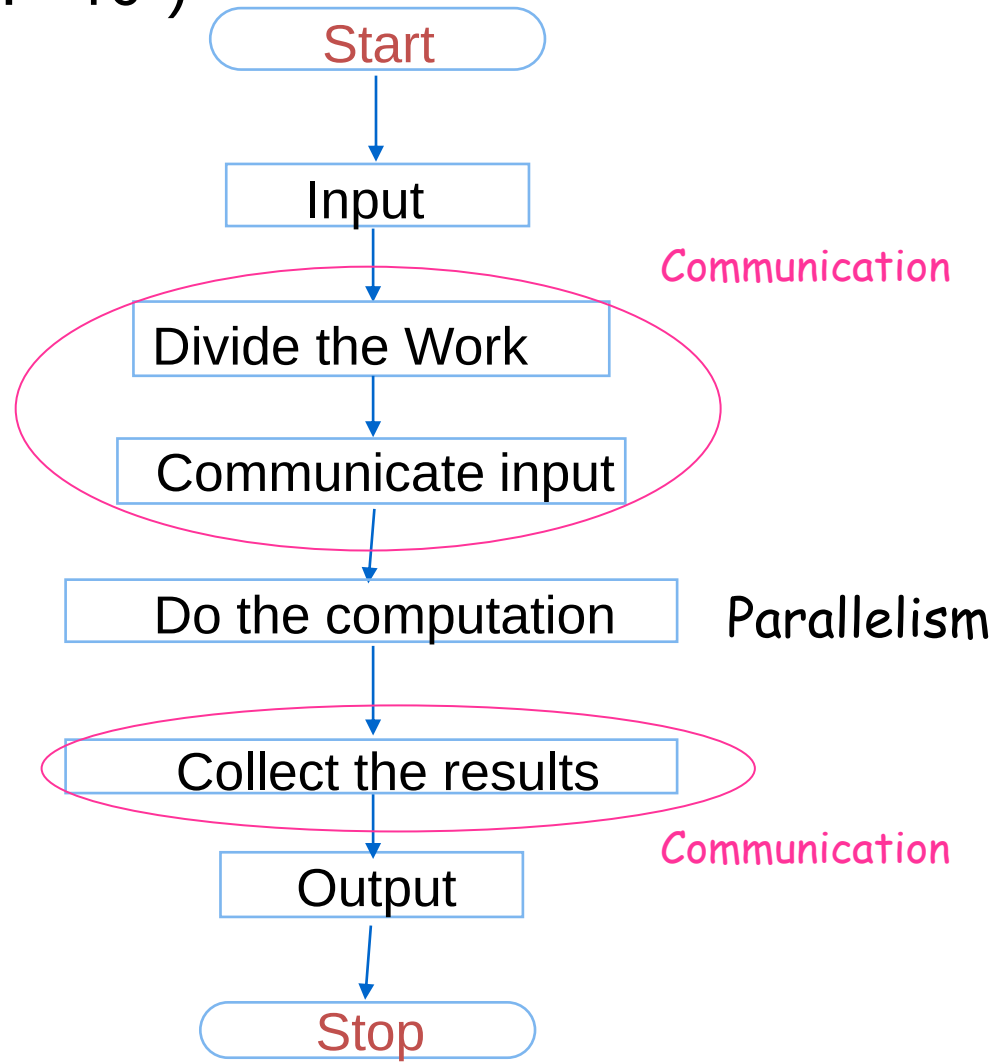
Contents

- General concepts
- About Message Passing Model
- What is MPI
- MPI Point-to-Point Communication
- MPI Datatypes

Serial vs Parallel Flow

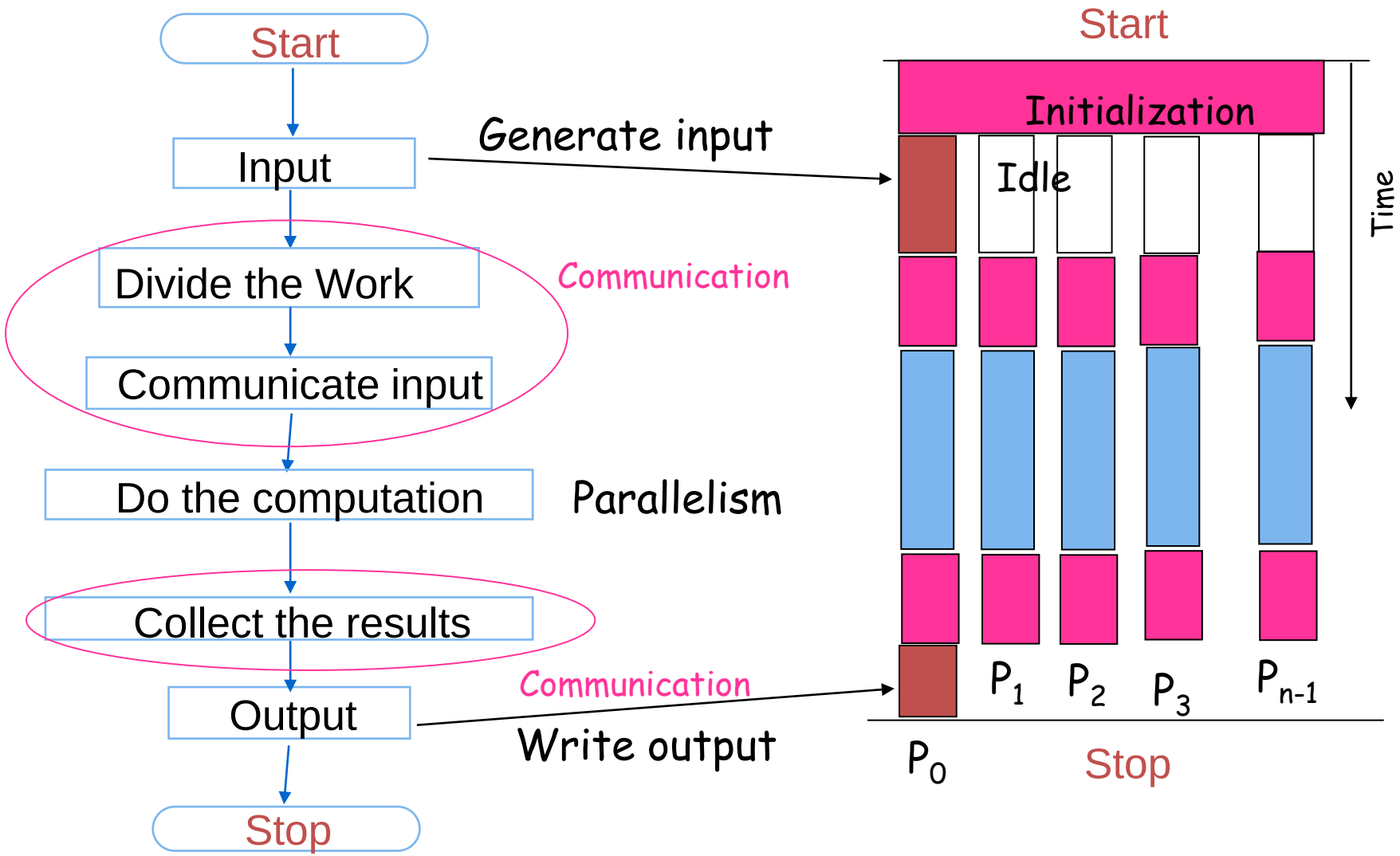
Compute $\sum x_i$ for (i=1,2,…… 10^9)





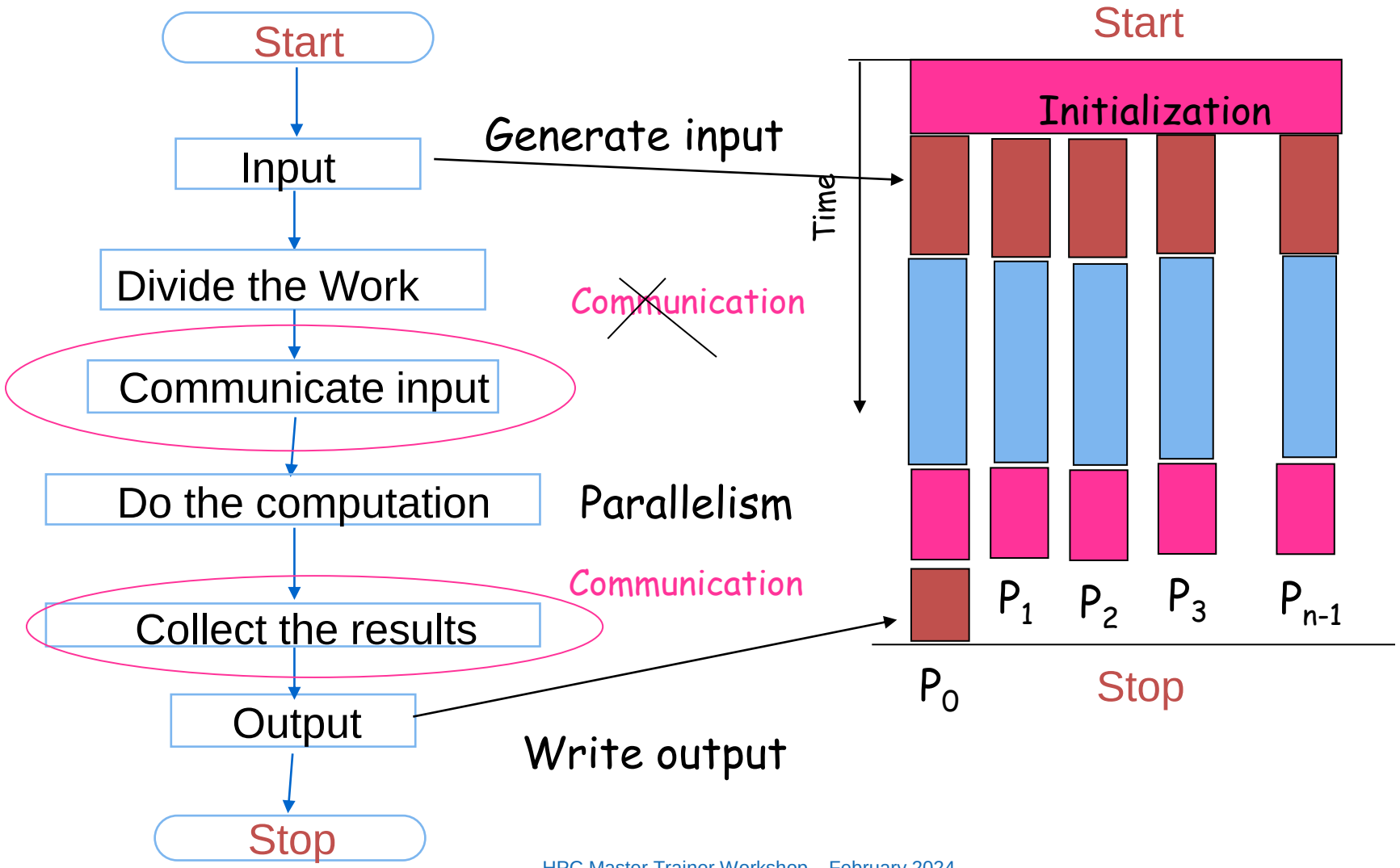
Serial vs Parallel Flow

Option 1: Read and Distribute inputs



Serial vs Parallel Flow

Option 2: Generate inputs simultaneously



Performance Metrics

1. Speed up $= \dfrac{\text{Time for sequential code}}{\text{Time for parallel code}}$

$$S_P = \frac{Ts}{Tp} \qquad 1 \leq S_P \leq P$$

2. Efficiency $E_P = \dfrac{Sp}{p}$ $\qquad 0 < E_P < 1$

$E_P = 1 \Rightarrow S_P = P$ $\qquad$ 100% efficient

Amdahl's Law

$$S = \frac{1}{f + (1-f) / P}$$

f = Sequential part of the code

Example $f = 0.1$ assume $P = 10$ processes

$$S = \frac{1}{0.1 + (0.9) / 10}$$

$$= \frac{1}{0.1 + (0.09)} \cong 5$$

As $P \longrightarrow \infty$ $S \longrightarrow 10$

Whatever we do, 10 is the maximum speedup possible

Communication Overheads

Latency

Startup time for each message transaction e.g. 1 μs

Bandwidth

The rate at which the messages are transmitted across the nodes / processors
e.g. 100 Gbits / sec.

Process and Thread

- An executing instance of a program is called a process
- Process has its independent memory space
- A thread is a subset of the process – also called lightweight process allowing faster context switching
- Threads share memory space within process's memory
- Threads may have some (usually small) private data
- A thread is an independent instruction stream, thus allowing concurrent operation
- In OpenMP one usually wants no more than one thread per core

Characteristics of Message Passing Model

- Separate memory address spaces
- Explicit data and work allocation by user
- Asynchronous parallelism
- Explicit interaction

How Message Passing Model Works

- A parallel computation consists of a number of processes
- Each process has purely local variables
- No mechanism for any process to directly access memory of another
- Sharing of data among processes is done by explicitly message passing
- Data transfer requires cooperative operations by each process
- Different processes need not be running on different processors

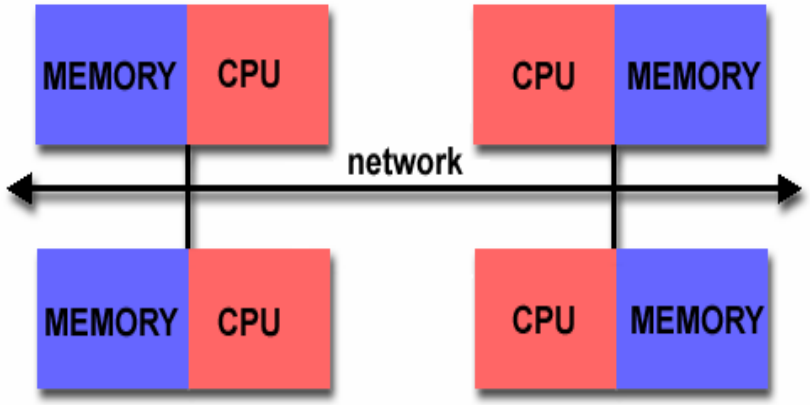
Usefulness of Message Passing Model

- Extremely general model
- Essentially, any type of parallel computation can be cast in the message passing form
- Can be implemented on wide variety of platforms, from networks of workstations to even single processor machines
- Generally allows more control over data location and flow within a parallel application than in, for example the shared memory model
- High performance

What is MPI ?

MPI stands for Message-Passing Interface

- MPI (Message-Passing Interface) is a message-passing library interface specification
- MPI addresses primarily the message-passing parallel programming model, in which data is moved from the address space of one process to that of another process through cooperative operations on each process.
- Extensions to the classical message-passing model are provided in collective operations, remote-memory access operations, dynamic process creation, threads and parallel I/O
- Every major HPC vendor have their own implementation of MPI
- However, programs written in message-passing style can run that supports such model
    - Distributed or shared-memory multi-processors
    - Networks of workstations
    - Single processor systems

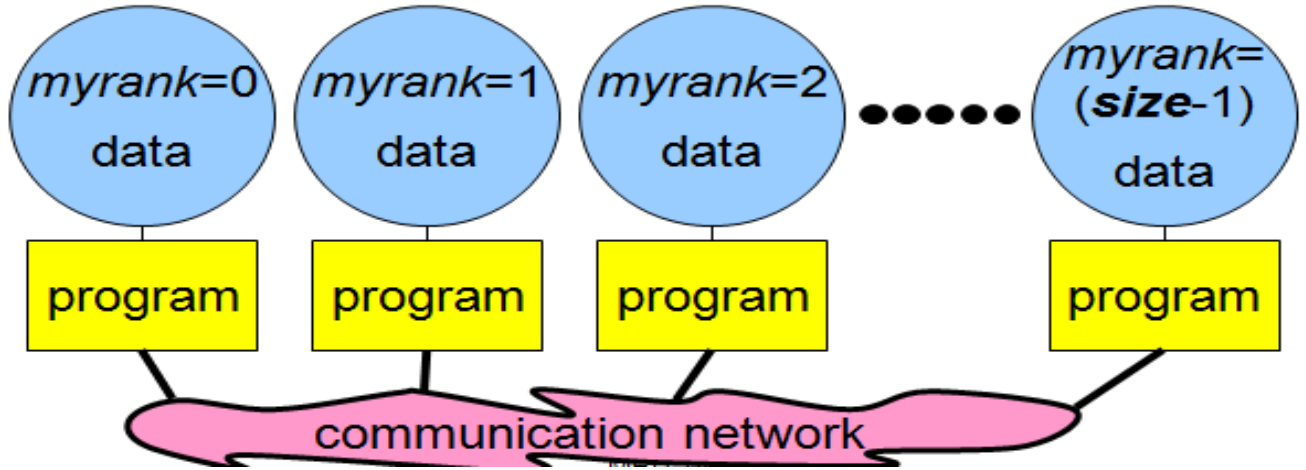


is MPI large or small ?

- MPI is Large (hundreds of functions)
  - Many features require extensive API
  - Complexity of use not related to number of functions
- MPI is small (6 basic functions)
  - All that's needed to get started are only 6 functions
- MPI is just right !
  - Flexibility available when required
  - Can start with small subset

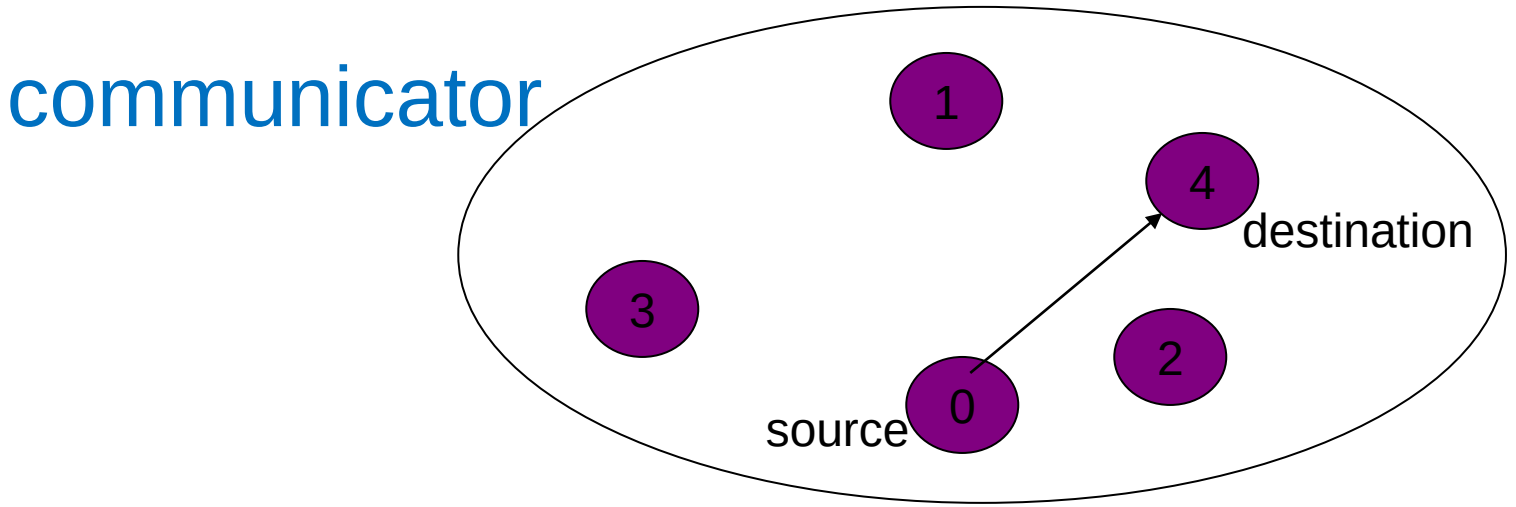
Data and Work Distribution

- Programmer imagines several processors, each with own memory, and writes a program to run on each processor
- To communicate together mpi-processes need unique identifiers: rank = identifying number
- all distribution decisions are based on the *rank*
  - like which process works on what data
  - which process works on what tasks



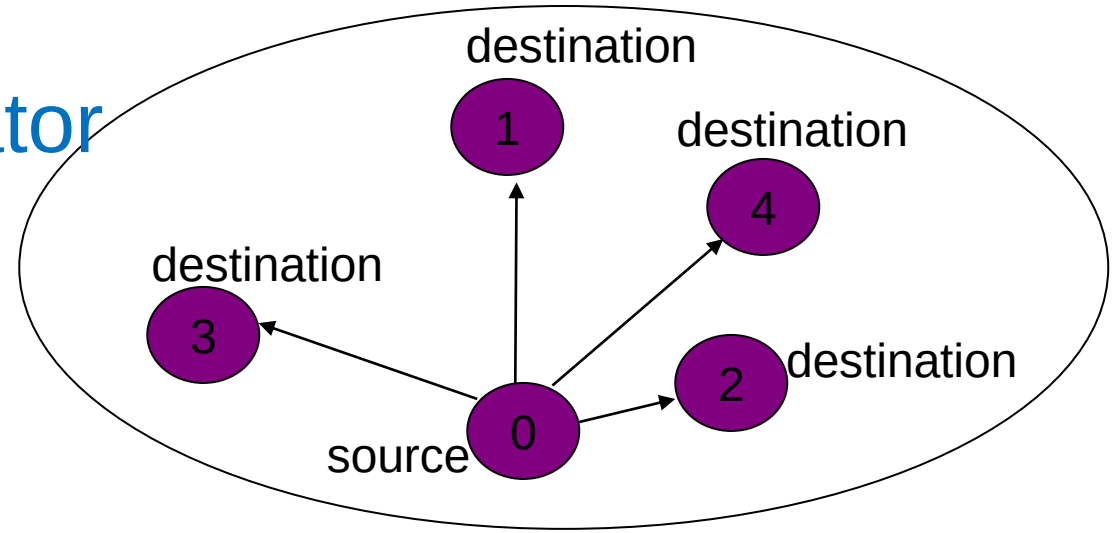
Point-to-Point Communication

- Communication between two processes
- Source process sends message to destination process
- Communication takes place within a communicator
- MPI_COMM_WORLD is default communicator



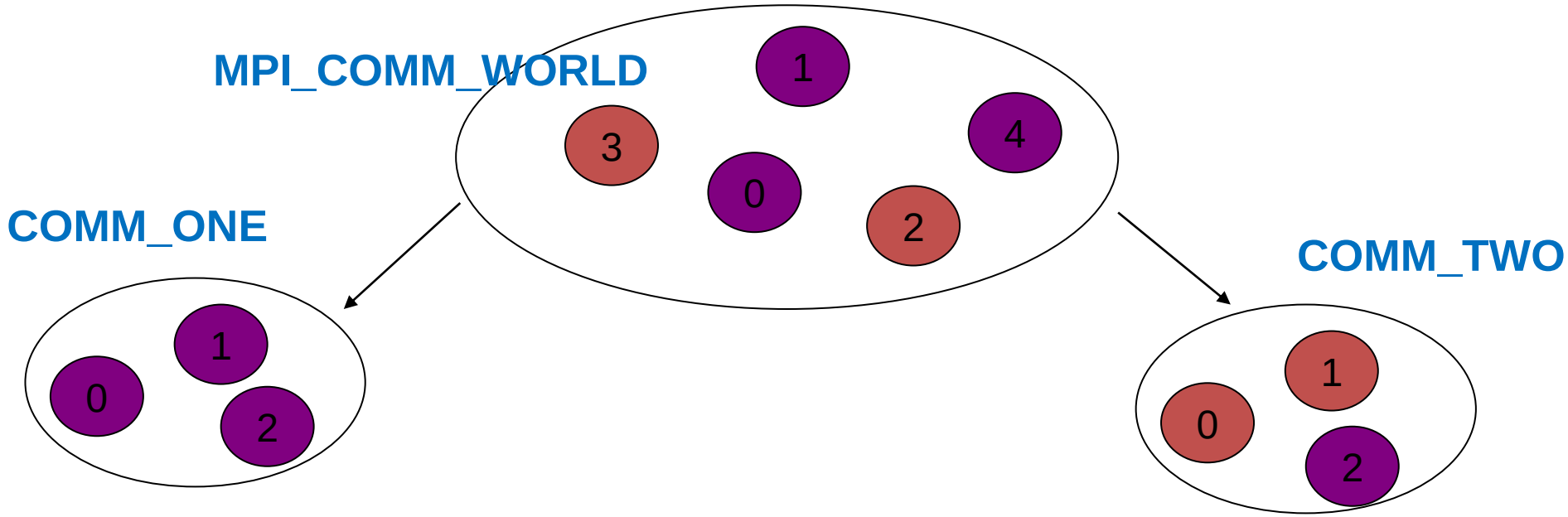
Collective Communication

- Communication between all processes
- A source process sends messages to or receives messages from all other processes
- Communication takes place within a communicator
- MPI_COMM_WORLD is default communicator



Communicators

- Is an object to handle a collection of processes
- Only processes within a communicator can talk among themselves
  - **ranks 0 to N-1**
- MPI_COMM_WORLD is default communicator containing all the processes
- User can create subsets of default communicators – overlapping or disjoint



Building blocks: Send and Recv

Basic operations in Message-passing programming paradigm are send and receive

```
send(void *sendbuf,  int noelems,  int dest)
```

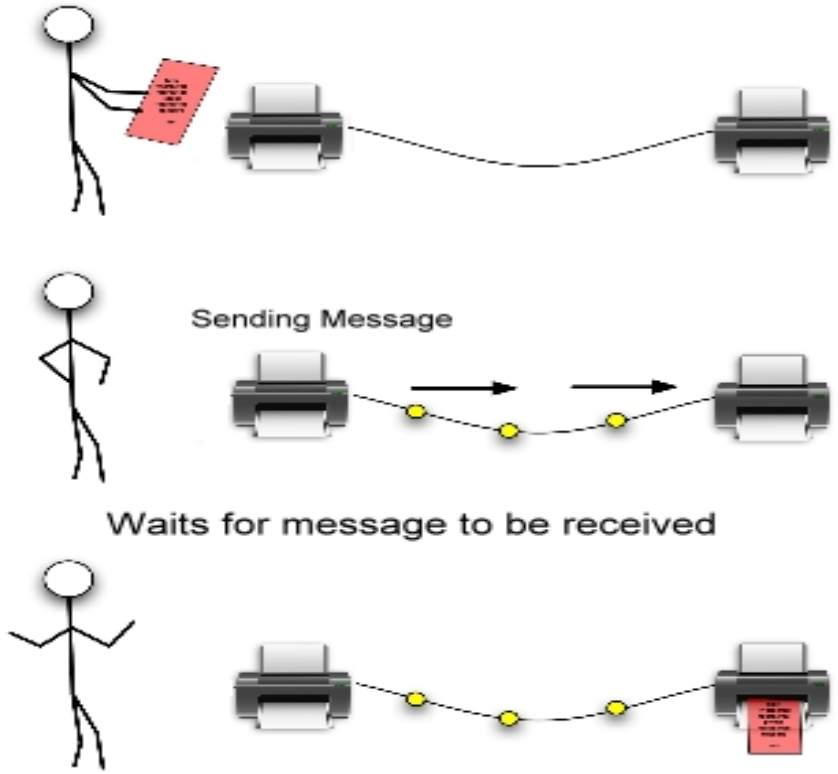
```
receive(void *recvbuf,  int noelems,  int source)
```

Building blocks: Send and Recv (contd….)

- “Completion” means that memory locations used in the message transfer can be safely accessed
    - send: variable sent can be modified after completion
    - receive: variable received can now be used
- MPI communication modes differ in what conditions on the receiving end are needed for completion
- Communication modes can be blocking or non-blocking
    - Blocking: return from function call implies completion
    - Non-blocking: routine returns immediately, completion to be tested for

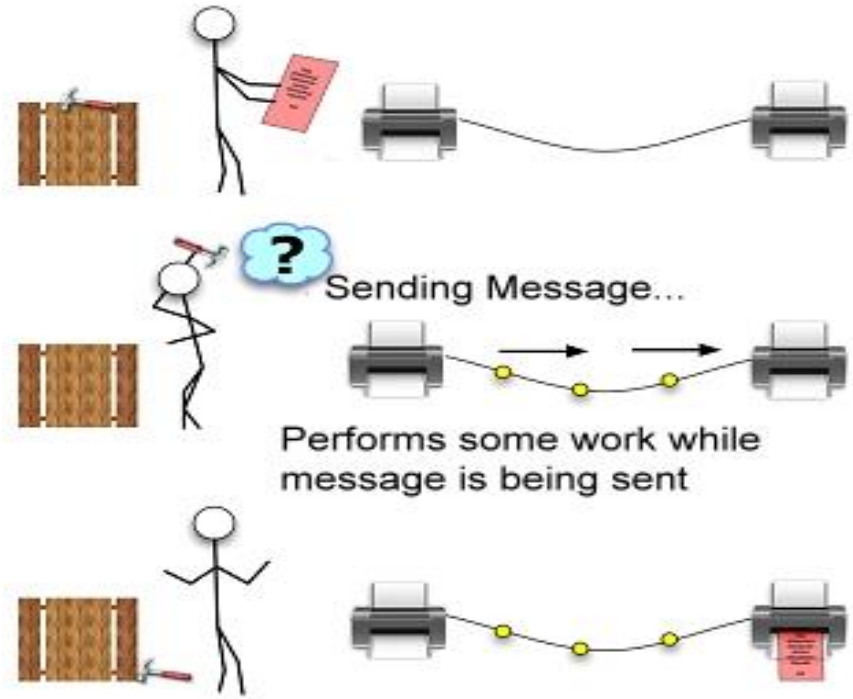
Blocking Operation

An operation that does not complete until the operation either succeeds or fails



Non-Blocking operation

An operation, such as sending or receiving a message, that returns immediately whether or not the operation was completed



Point to Point Communication

- Message is sent from a sending process to a receiving process. Only these two process need to know anything about the message.

- Message passing system provides following information to specify the message transfer
    - Which process is sending the message
    - Where is the data on the sending process
    - What kind of data is being sent
    - How much data is there
    - Which process is receiving the message
    - Where should the data be left on the receiving process
    - How much data is receiving process prepared to accept

General MPI Program Structure

MPI include file

.
.
.

Initialize MPI environment

.
.
.

Do work and make message passing calls

.
.
.

Terminate MPI Environment

Header files and calls format

- MPI constants, macros, definitions, function prototypes and handles are defined in a header file
- Required for all programs/routines which make MPI library calls

C (case sensitive):

```
# include “mpi.h”

error = MPI_Xxxxx(parameter,...);
```

Fortran (case unimportant):

```
include “mpif.h”

CALL MPI_XXXXX(parameter,...,IERROR)
```

Starting With MPI Programming

- Six basic functions to start :

1. MPI_INIT	Initialize MPI Environment
2. MPI_FINALIZE	Finish MPI Environment
3. MPI_COMM_RANK	Get the process rank
4. MPI_COMM_SIZE	Get the number of processes
5. MPI_Send	Send data to another process
6. MPI_Recv	Get data from another process

Initializing MPI

- MPI_Init is the first MPI routine called (only once)
- Initializes the MPI environment

C: int MPI_Init(int *argc, char ***argv)

Communicator Size

- How many processes are contained within a communicator?

C: MPI_Comm_size (MPI_Comm comm, int *size)

Process Rank

- Process ID number within the communicator
  - Starts with zero and goes to (n - 1) where n is the number of processes requested
- Used to identify the source and destination of messages

C: MPI_Comm_rank(MPI_Comm comm, int *rank)

Exiting MPI

- Performs various clean-ups tasks to terminate the MPI environment.
- Always called at end of the computation.

C: MPI_Finalize()

Note : If any one process does not reach the finalization statement, the program will appear to hang.

Example program: hello_world.c

```
#include "mpi.h"
#include <stdio.h>
int main( argc, argv)
int argc; char **argv;
{
int rank, size;
MPI_Init( &argc, &argv );
MPI_Comm_rank(MPI_COMM_WORLD, &rank );
MPI_Comm_size(MPI_COMM_WORLD, &size );
/* Your code here */
printf("Hello world! I'm %d of %d\n", rank, size);
MPI_Finalize();
return 0;
}
```

Header File

Communicator

Initializing MPI

Rank

Size

Exiting MPI

Example program 1: hello_world.f

```
program hello
include 'mpif.h'

integer rank, size, ierror, tag, status(MPI_STATUS_SIZE)

call MPI_INIT(ierror)
call MPI_COMM_SIZE(MPI_COMM_WORLD, size, ierror)
call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierror)

print*, 'node', rank, ': Hello world '

call MPI_FINALIZE(ierror)

end
```

How to Compile &Execute MPI Programs ?

To Compile : mpicc hello_world.c -o hello

mpif90 hello_world.f -o hello

To run with 4 processes : mpiexec -np 4 hello

Output Hello world! I'm 2 of 4

Hello world! I'm 1 of 4

Hello world! I'm 3 of 4

Hello world! I'm 0 of 4

Note - Order of output is not specified by MI

MPI Send

```
int MPI_Send( void *buf,          // Data To be sent
              int count,          // Total Data Elements to be sent
MPI_Datatype datatype,            // Datatype of the data to be sent
              int dest,           // Processor to which data is being sent
              int tag,            // To distinguish from diff types of msg
          MPI_Comm comm)          // Communicator
```

MPI Receive

```
int MPI_Recv(void *buf,     // Data To be Receive
             int count,     // Total Data Elements to be recv
MPI_Datatype datatype,  // Datatype of the data to be recv
             int source,    // Processor from where data is being sent
             int tag,       // To distinguish from diff types of msg
         MPI_Comm comm,     // Communicator
        MPI_Status *status)    // Status structure
```

Wildcards

- Allow you to not necessarily specify a tag or source
  - Eg :MPI_ANY_SOURCE and MPI_ANY_TAG are wild cards
- Status structure is used to get wildcard values
  - The tag of a received message

    C : status.MPI_TAG
  - The source of a received message

    C : status.MPI_SOURCE
  - The error code of the MPI call

    C : status.MPI_ERROR

MPI Status

Accessing status information

- The tag of a received message
  - C : status.MPI_TAG
  - Fortran : STATUS(MPI_TAG)
- The source of a received message
  - C : status.MPI_SOURCE
  - Fortran : STATUS(MPI_SOURCE)
- The error code of the MPI call
  - C : status.MPI_ERROR
  - Fortran : STATUS(MPI_ERROR)

Message Datatype

- A message contains an array of elements or scalar element of some particular MPI datatype
- MPI datatypes:
  - Basic types
  - Derived types
- Derived types can be build up from basic types

MPI DataTypes

C Data Types		Fortran Data Types	
MPI_CHAR	signed char	MPI_CHARACTER	character(1)
MPI_SHORT	signed short int		
MPI_INT	signed int	MPI_INTEGER	integer
MPI_LONG	signed long int		
MPI_UNSIGNED_CHAR	unsigned char		
MPI_UNSIGNED_SHORT	unsigned short int		
MPI_UNSIGNED	unsigned int		
MPI_UNSIGNED_LONG	unsigned long int		
MPI_FLOAT	float	MPI_REAL	real
MPI_DOUBLE	double	MPI_DOUBLE_PRECISION	double precision
MPI_LONG_DOUBLE	long double		
		MPI_COMPLEX	complex
		MPI_DOUBLE_COMPLEX	double complex
		MPI_LOGICAL	logical
MPI_BYTE	8 binary digits	MPI_BYTE	8 binary digits
MPI_PACKED	data packed or unpacked with MPI_Pack()/ MPI_Unpack	MPI_PACKED	data packed or unpacked with MPI_Pack()/ MPI_Unpack

Sending a Message

- int MPI_Send(void *buf, int count, MPI_Datatype datatype, int dest, int tag, MPI_Comm comm)
  - buf: starting address of the data to be sent
  - count: number of elements to be sent (not bytes)
  - datatype: MPI datatype of each element
  - dest: rank of destination process
  - tag: message identifier (set by user)
  - comm: MPI communicator of processors involved
- MPI_Send(data, 500, MPI_FLOAT, 5, 25, MPI_COMM_WORLD)

Receiving a Message

- int MPI_Recv(void *buf, int count, MPI_Datatype datatype, int source, int tag, MPI_Comm comm, MPI_Status *status)
  - buf: starting address of buffer where the data is to be stored
  - count: number of elements to be received (not bytes)
  - datatype: MPI datatype of each element
  - source: rank of source process
  - tag: message identifier (set by user)
  - comm: MPI communicator of processors involved
  - status: structure of information about the message that is returned

- MPI_Recv(buffer, 500, MPI_FLOAT, 3, 25, MPI_COMM_WORLD, status)

Blocking Communication Functions

Mode	MPI Function
Standard send	MPI_Send
Synchronous send	MPI_Ssend
Buffered send	MPI_Bsend
Ready send	MPI_Rsend
Receive	MPI_Recv

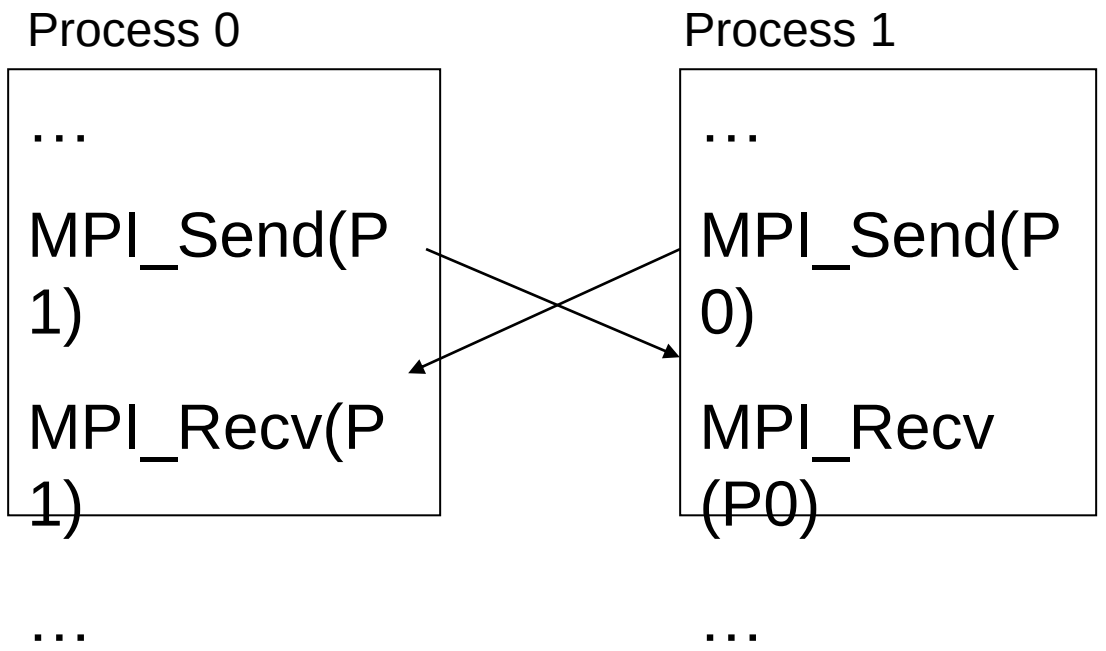
Similar variants exist for non-blocking calls also

For a Communication to Succeed

- Sender must specify a valid destination rank
- Receiver must specify a valid source rank
- The communicator must be the same
- Tags must match
- Receiver’s buffer must be large enough
- User-specified buffer should be large enough (buffered send only)
- Receive posted before send (ready send only)

Deadlocks

- A deadlock occurs when two or more processors try to access the same set of resources
- Deadlocks are possible in blocking communication
  - Example: Two processors initiate a blocking send to each other without posting a receive



MPI Programming Style

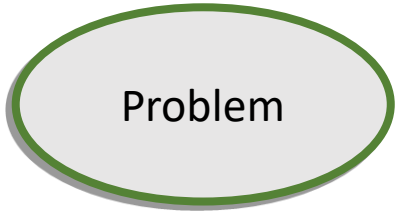
SPMD : Single program multiple data

Each process executes the same program but with different input data

MPMD : Multiple programs multiple data

Different processes may execute different programs

Methodology to Develop Parallel Applications



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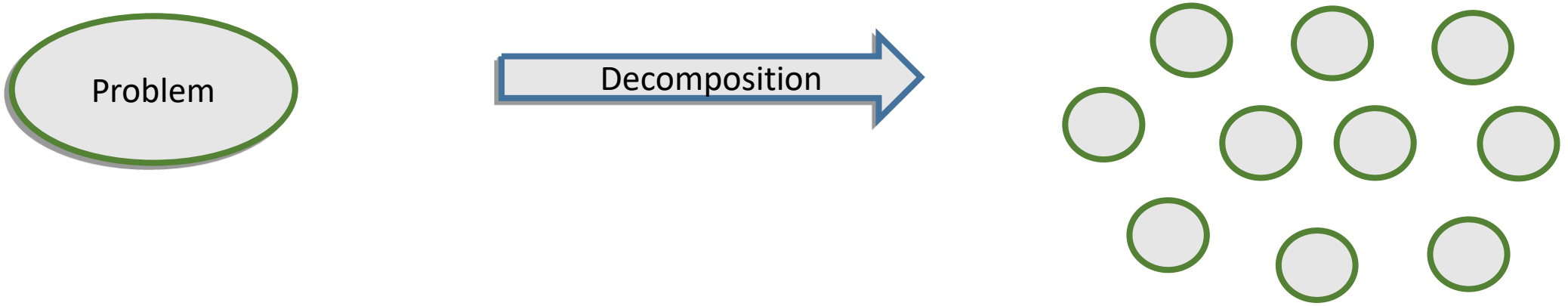

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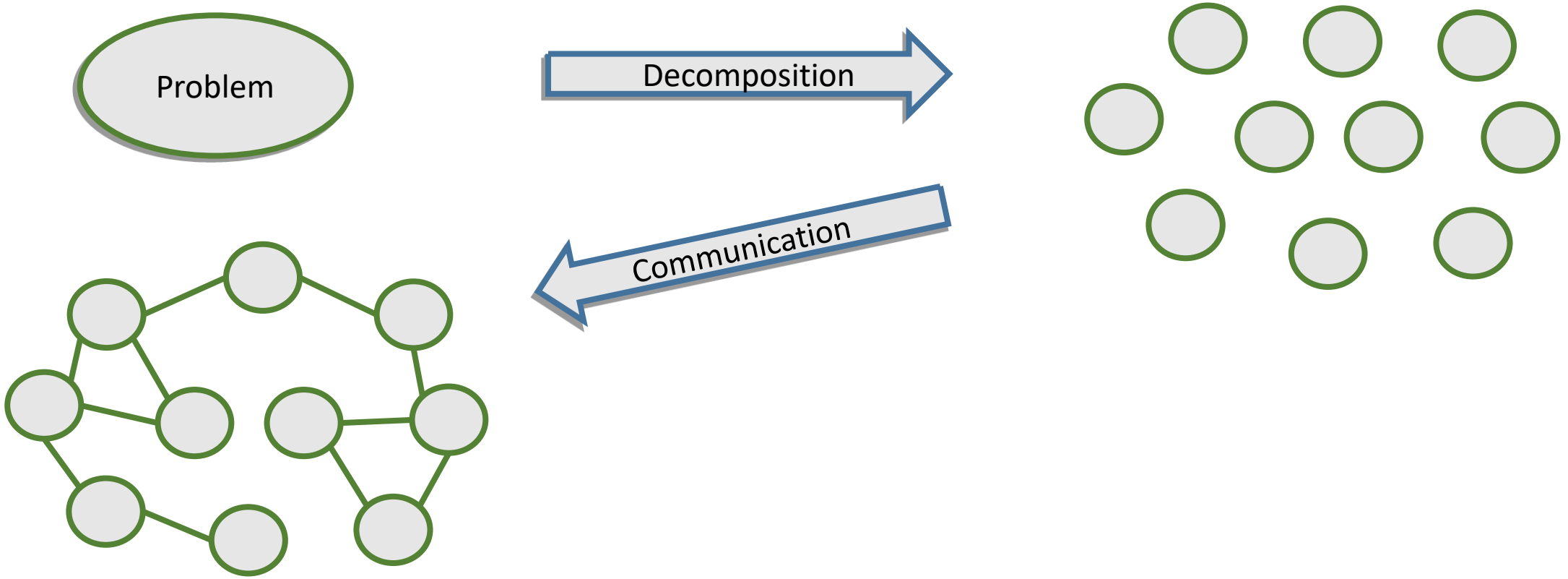

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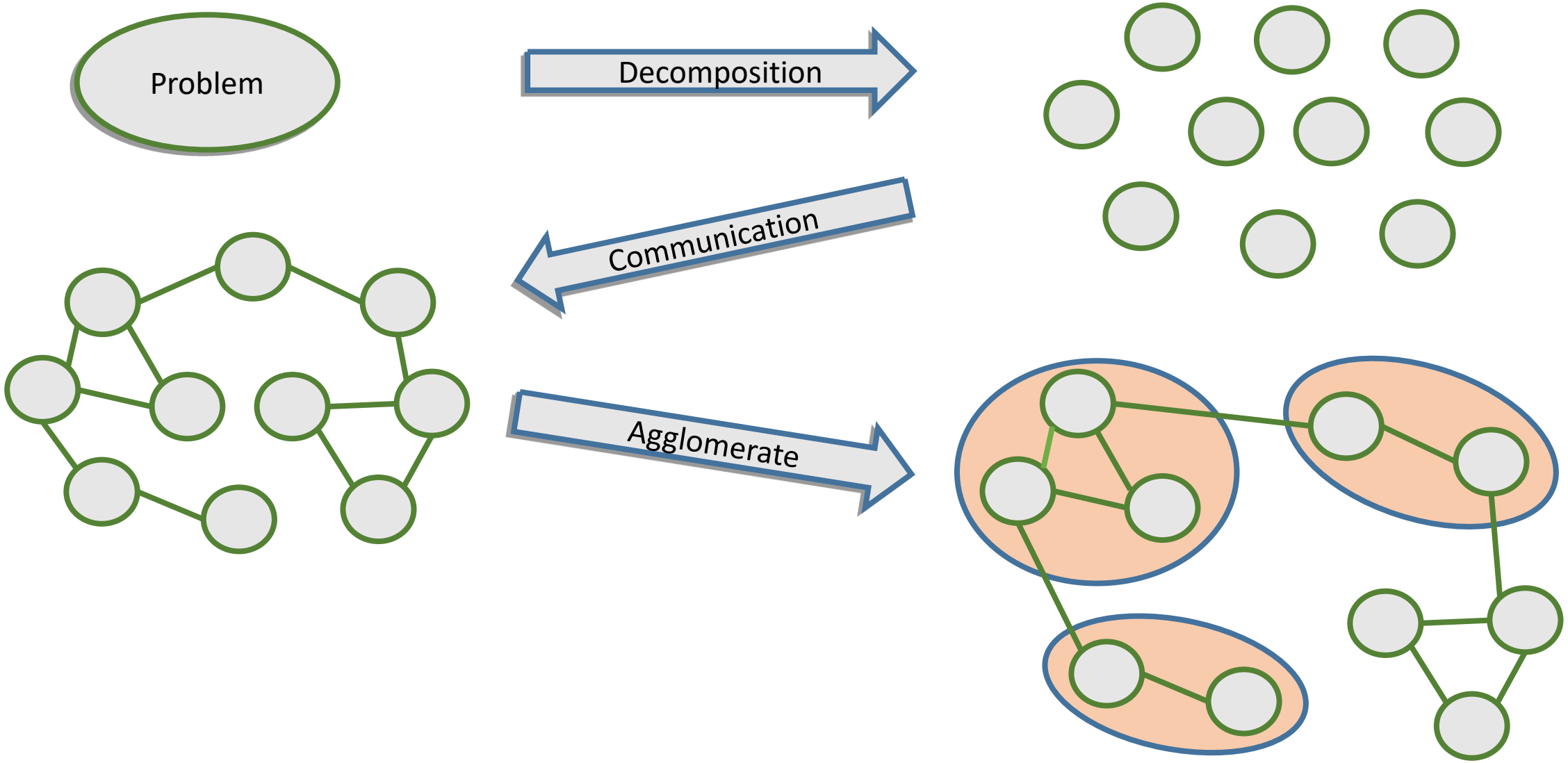

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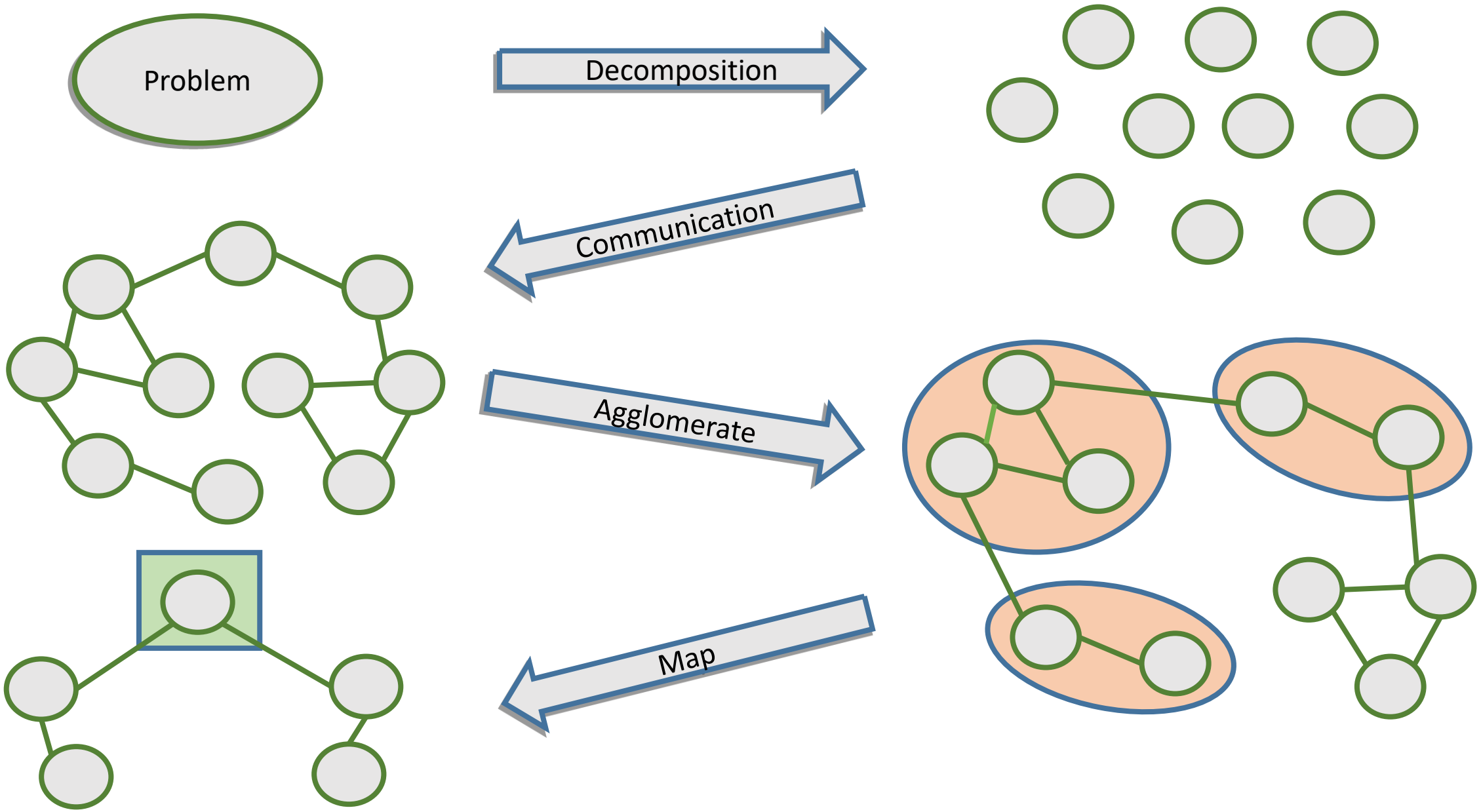
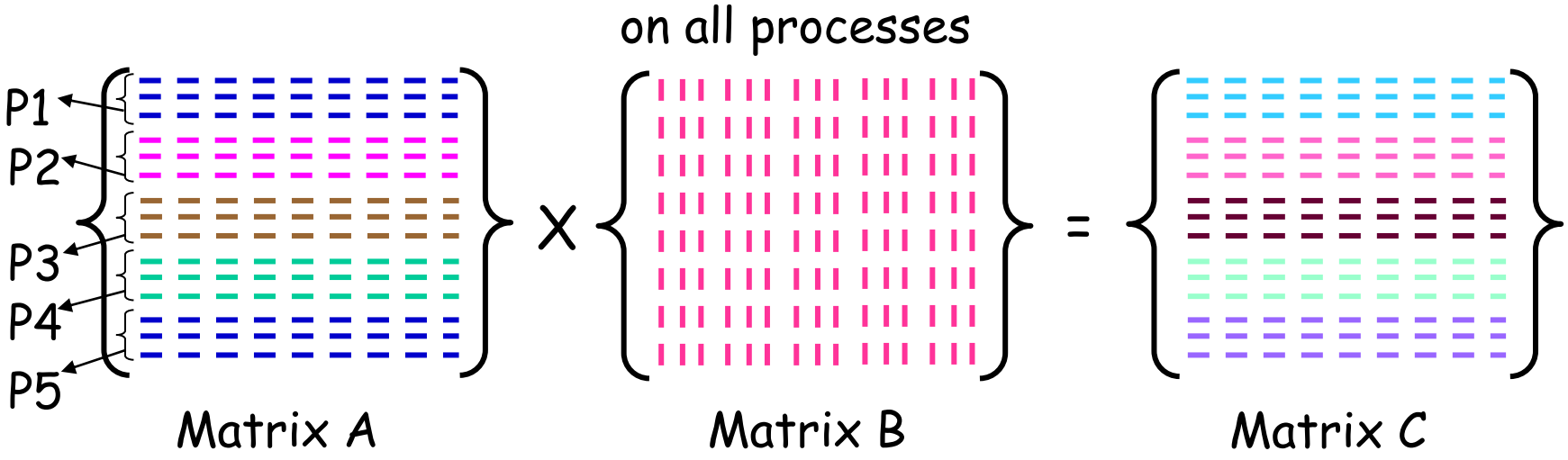


Defensive Matrix Multiplication

- The master process is the controller process that
  - Distributes Matrix A (row-wise) to each worker process
  - Communicates complete Matrix B to each worker process
- Each worker multiplies assigned rows of matrix A with matrix B
- Master process collects resultant Matrix C from each worker process.



Example program: Matrix-Matrix Multiply

```
#define NRA 50 /* Rows in Matrix A */
#define NCA 40 /* Columns in Matrix A */
#define NCB 30 /* Columns in Matrix B */
#include "mpi.h"
#include <stdio.h>

int main(int argc, int *argv[])
{
  int numtasks,taskid; /* No.of tasks and task identifier */
  int source,dest      /* Task id of message source and destination*/
  double a[NRA][NCA],b[NCA][NCB],c[NRA][NCB]; /* Matrix A, B, C */
  rows,averow,extra,offset,numworkers,i,j,k,rc; /* Miscellaneous */
  MPI_Status status;

  rc = MPI_Init(&argc,&argv);
  rc|= MPI_Comm_size(MPI_COMM_WORLD,&numtasks);
  rc|= MPI_Comm_rank(MPI_COMM_WORLD,&taskid);
  if (rc != 0)printf("\nError initializing MPI or Task ID\n");
  else printf("\nTask ID = %d\n", taskid);
  numworkers = numtasks-1;
```

Master process

```
if(taskid == 0)
{
  printf("Number of worker tasks = %d\n",numworkers);
  for (i=0; i<NRA; i++)   /* Generate data for Matrix A & B */
    for (j=0; j<NCA; j++)a[i][j]= i+j;
  for (i=0; i<NCA; i++)
    for (j=0; j<NCB; j++)b[i][j]= i*j;

  averow = NRA/numworkers;
  extra = NRA%numworkers;
  offset = 0;
  for (dest=1; dest<=numworkers; dest++)
  {
    rows = (dest <= extra) ? averow+1 : averow;
    printf("\nSending %d rows to task %d\n",rows,dest);
    MPI_Send(&offset,      1,       MPI_INT,   dest,1,MPI_COMM_WORLD);
    MPI_Send(&rows,        1,       MPI_INT,   dest,1,MPI_COMM_WORLD);
    MPI_Send(&a[offset][0],rows*NCA,MPI_DOUBLE,dest,1,MPI_COMM_WORLD);
    MPI_Send(&b,           NCA*NCB, MPI_DOUBLE,dest,1,MPI_COMM_WORLD);
    offset = offset + rows;
   }
```

Master process (contd…)

```
  for (i=1; i<=numworkers; i++) /* Wait for results from workers */
  {
    source = i;
    MPI_Recv(&offset,1,MPI_INT,source,2,MPI_COMM_WORLD,&status);
    MPI_Recv(&rows,  1,MPI_INT,source,2,MPI_COMM_WORLD,&status);
    MPI_Recv(&c[offset][0],rows*NCB,MPI_DOUBLE,source,2,
             MPI_COMM_WORLD, &status);
  }

  printf("Here is the result matrix\n"); /* Print Results */
  for (i=0; i<NRA; i++)
  {
    printf("\n");
    for (j=0; j<NCB; j++)
      printf("%6.2f ", c[i][j]);
  }
  printf ("\n");
}
```

Worker processes

```
if (taskid > 0) /* Worker Tasks */
{
  MPI_Recv(&offset,1,       MPI_INT,    0,1,MPI_COMM_WORLD,&status);
  MPI_Recv(&rows,  1,       MPI_INT,    0,1,MPI_COMM_WORLD,&status);
  MPI_Recv(&a,     rows*NCA,MPI_DOUBLE, 0,1,MPI_COMM_WORLD,&status);
  MPI_Recv(&b,     NCA*NCB, MPI_DOUBLE, 0,1,MPI_COMM_WORLD,&status);
  for (k=0; k<NCB; k++)
    for (i=0; i<rows; i++)
    {
      c[i][k] = 0.0;
      for (j=0; j<NCA; j++)
        c[i][k] = c[i][k] + a[i][j] * b[j][k];
    }
  MPI_Send(&offset, 1,        MPI_INT,    0, 2, MPI_COMM_WORLD);
  MPI_Send(&rows,   1,        MPI_INT,    0, 2, MPI_COMM_WORLD);
  MPI_Send(&c,      rows*NCB, MPI_DOUBLE, 0, 2, MPI_COMM_WORLD);
}
 MPI_Finalize();
} /* End main */
```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Thank You
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